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IS 10593 (2006): Mineral Oil-impregnated electrical equipment in services - Guide to the interpretation of dissolved and free gases analysis [ETD 3: Fluids for Electrotechnical Applications]

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भारतीय मानक

सेवा में खनिज तेल-संसिक्त विद्युत उपस्कर —
घुलित और मुक्त गैसों के विश्लेषण की व्याख्या की मार्गदर्शिका
(दूसरा पुनरीक्षण)

Indian Standard

MINERAL OIL-IMPREGNATED ELECTRICAL
EQUIPMENT IN SERVICE — GUIDE TO THE
INTERPRETATION OF DISSOLVED
AND FREE GASES ANALYSIS

(*Second Revision*)

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NEW DELHI 110002

NATIONAL FOREWORD

This Indian Standard (Second Revision) which is identical with IEC 60599 (1999) 'Mineral oil-impregnated electrical equipment in service — Guide to the interpretation of dissolved and free gases analysis' issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendation of the Fluids for Electrotechnical Applications Sectional Committee and approval of the Electrotechnical Division Council.

The text of the IEC Standard has been approved as suitable for publication as an Indian Standard without deviations. Certain conventions are, however, not identical to those used in Indian Standards. Attention is particularly drawn to the following:

- a) Wherever the words 'International Standard' appear referring to this standard, they should be read as 'Indian Standard'.
- b) Comma (,) has been used as a decimal marker while in Indian Standards, the current practice is to use a point (.) as the decimal marker.

In this adopted standard, references appear to certain International Standards for which Indian Standards also exist. The corresponding Indian Standards, which are to be substituted in their respective places are listed below along with their degree of equivalence for the editions indicated:

<i>International Standard</i>	<i>Corresponding Indian Standard</i>	<i>Degree of Equivalence</i>
IEC 60050 (212) (1990) International Electrotechnical Vocabulary (IEV) — Chapter 212 : Insulating solids, liquids and gases	IS 1885 (Part 62) : 1993 Electrotechnical vocabulary: Part 62 Insulating solids, liquids and gases (<i>first revision</i>)	Identical
IEC 60050 (604) (1987) International Electrotechnical Vocabulary (IEV) — Chapter 604 : Generation, transmission and distribution of electricity — Operation	IS 1885 (Part 70) : 1993 Electrotechnical vocabulary: Part 70 Generation, transmission and distribution of electricity — Operation	do
IEC 60567 (1992) Guide for the sampling of gases and of oil-filled electrical equipment and for the analysis of free and dissolved gases	IS 9434 : 1992 Guide for the sampling and analysis of free and dissolved gases and oil from oil-filled electrical equipment (<i>first revision</i>)	Technically Equivalent

The technical committee responsible for the preparation of this standard has reviewed the provisions of following International Standards referred to in this adopted standard and has decided that they are acceptable for use in conjunction with this standard:

<i>International Standard</i>	<i>Title</i>
IEC 60050 (191) (1990)	International Electrotechnical Vocabulary (IEV) — Chapter 191 : Dependability and quality of service
IEC 61198 (1993)	Mineral insulating oils — Methods for the determination of 2-furfural and related compounds

Only the English language text of the IEC Publication has been retained while adopting it is an Indian Standard and as such the page numbers given here are not same as in IEC publications.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated expressing the result of a test, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*)'. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

MINERAL OIL-IMPREGNATED ELECTRICAL EQUIPMENT IN SERVICE — GUIDE TO THE INTERPRETATION OF DISSOLVED AND FREE GASES ANALYSIS

(Second Revision)

This International Standard is a guide describing how the concentrations of dissolved gases or free gases may be interpreted to diagnose the condition of oil-filled electrical equipment in service and suggest future action.

This guide is applicable to electrical equipment filled with mineral insulating oil and insulated with cellulosic paper or pressboard-based solid insulation. Information about specific types of equipment such as transformers (power, instrument, industrial, railways, distribution), reactors, bushings, switchgear and oil-filled cables is given only as an indication in the application notes (see annex A).

The Guide may be applied only with caution to other liquid-solid insulating systems.

In any case, the indications obtained should be viewed only as guidance and any resulting action should be undertaken only with proper engineering judgment.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All normative documents are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60050(191):1990, *International Electrotechnical Vocabulary (IEV) – Chapter 191: Dependability and quality of service*

IEC 60050(212):1990, *International Electrotechnical Vocabulary (IEV) – Chapter 212: Insulating solids, liquids and gases*

IEC 60050(604):1987, *International Electrotechnical Vocabulary (IEV) – Chapter 604: Generation, transmission and distribution of electricity – Operation*

IEC 60567:1992, *Guide for the sampling of gases and of oil from oil-filled electrical equipment and for the analysis of free and dissolved gases*

IEC 61198:1993, *Mineral insulating oils – Methods for the determination of 2-furfural and related compounds*

3 Definitions and abbreviations

3.1 Definitions

For the purpose of this International Standard, the following definitions, some of them based on IEC 60050(191), IEC 60050(212) and IEC 60050(604) apply:

3.1.1

fault

an unplanned occurrence or defect in an item which may result in one or more failures of the item itself or of other associated equipment [IEV 604-02-01]

NOTE – In electrical equipment, a fault may or may not result in damage to the insulation and failure of the equipment.

3.1.2

non-damage fault

a fault which does not involve repair or replacement action at the point of the fault
[IEV 604-02-09]

NOTE – Typical examples are self-extinguishing arcs in switching equipment or general overheating without paper carbonization.

3.1.3

damage fault

a fault which involves repair or replacement action at the point of the fault
[IEV 604-02-08, modified]

3.1.4

incident

an event related to an internal fault which temporarily or permanently disturbs the normal operation of an equipment [IEV 604-02-03, modified]

NOTE – Typical examples are gas alarms, equipment tripping or equipment leakage.

3.1.5

failure

the termination of the ability of an item to perform a required function [IEV 191-04-01]

NOTE – In the electrical equipment, failure will result from a damage fault or incident necessitating outage, repair or replacement of the equipment, such as internal breakdown, rupture of tank, fire or explosion.

3.1.6

electrical fault

a partial or disruptive discharge through the insulation

3.1.7

partial discharge

a discharge which only partially bridges the insulation between conductors. It may occur inside the insulation or adjacent to a conductor [IEV 212-01-34, modified]

NOTE 1 – Corona is a form of partial discharge that occurs in gaseous media around conductors which are remote from solid or liquid insulation. This term is not to be used as a general term for all forms of partial discharges.

NOTE 2 – X-wax is a solid material which is formed from mineral insulating oil as a result of electrical discharges and which consists of polymerized fragments of the molecules of the original liquid [IEV 212-07-24, modified]. Comparable products may be formed from other liquids under similar conditions.

NOTE 3 – Sparking of low energy, for example because of metals or floating potentials, is sometimes described as partial discharge but should rather be considered as a discharge of low energy.

3.1.8

discharge (disruptive)

the passage of an arc following the breakdown of the insulation [IEV 604-03-38, modified]

NOTE 1 – Discharges are often described as arcing, breakdown or short circuits. The more specific following terms are also used:

- sparkover (discharge through the oil);
- puncture (discharge through the solid insulation);
- flashover (discharge at the surface of the solid insulation);
- tracking (the progressive degradation of the surface of solid insulation by local discharges to form conducting or partially conducting paths);
- sparking discharges which, in the conventions of physics, are local dielectric breakdowns of high ionization density or small arcs.

NOTE 2 – Depending on the amount of energy contained in the discharge, it will be described as a discharge of low or high energy, based on the extent of damage observed on the equipment (see 5.2).

3.1.9

thermal fault

excessive temperature rise in the insulation

NOTE – Typical causes are

- insufficient cooling,
- excessive currents circulating in adjacent metal parts (as a result of bad contacts, eddy currents, stray losses or leakage flux),
- excessive currents circulating through the insulation (as a result of high dielectric losses), leading to a thermal runaway,
- overheating of internal winding or bushing connection lead.

3.1.10

typical values of gas concentrations

gas concentrations normally found in the equipment in service which have no symptoms of failure, and which are overpassed by only an arbitrary percentage of higher gas contents, for example 10 % (see 8.2.1)

NOTE 1 – Typical values will differ in different types of equipment and in different networks, depending on operating practices (load levels, climate, etc.).

NOTE 2 – Typical values, in many countries and by many users, are quoted as "normal values", but this term has not been used here to avoid possible misinterpretations.

3.2 Abbreviations

3.2.1 Chemical names and symbols

Name	Symbol
Nitrogen	N ₂
Oxygen	O ₂
Hydrogen	H ₂
Carbon monoxide	CO
Carbon dioxide	CO ₂
Methane	CH ₄
Ethane	C ₂ H ₆
Ethylene	C ₂ H ₄
Acetylene	C ₂ H ₂

3.2.2 General abbreviations

DGA: Dissolved gas analysis

CIGRE: Conférence Internationale des Grands Réseaux Électriques

S: Analytical detection limit

4 Mechanisms of gas formation

4.1 Decomposition of oil

Mineral insulating oils are made of a blend of different hydrocarbon molecules containing CH₃, CH₂ and CH chemical groups linked together by carbon-carbon molecular bonds. Scission of some of the C-H and C-C bonds may occur as a result of electrical and thermal faults, with the formation of small unstable fragments, in radical or ionic form, such as H[•], CH₃[•], CH₂[•], CH[•] or C[•] (among many other more complex forms), which recombine rapidly, through complex reactions, into gas molecules such as hydrogen (H-H), methane (CH₃-H), ethane (CH₃-CH₃), ethylene (CH₂ = CH₂) or acetylene (CH ≡ CH). C₃ and C₄ hydrocarbon gases, as well as solid particles of carbon and hydrocarbon polymers (X-wax), are other possible recombination products. The gases formed dissolve in oil, or accumulate as free gases if produced rapidly in large quantities, and may be analyzed by DGA according to IEC 60567.

Low-energy faults, such as partial discharges of the cold plasma type (corona discharges), favour the scission of the weakest C-H bonds (338 kJ/mole) through ionization reactions and the accumulation of hydrogen as the main recombination gas. More and more energy and/or higher temperatures are needed for the scission of the C-C bonds and their recombination into gases with a C-C single bond (607 kJ/mole), C=C double bond (720 kJ/mole) or C≡C triple bond (960 kJ/mole), following processes bearing some similarities with those observed in the petroleum oil-cracking industry.

Ethylene is thus favoured over ethane and methane above temperatures of approximately 500 °C (although still present in lower quantities below). Acetylene requires temperatures of at least 800 °C to 1 200 °C, and a rapid quenching to lower temperatures, in order to accumulate as a stable recombination product. Acetylene is thus formed in significant quantities mainly in arcs, where the conductive ionized channel is at several thousands of degrees Celsius, and the interface with the surrounding liquid oil necessarily below 400 °C (above which oil vaporizes completely), with a layer of oil vapour/decomposition gases in between. Acetylene may still be formed at lower temperatures (< 800 °C), but in very minor quantities. Carbon particles form at 500 °C to 800 °C and are indeed observed after arcing in oil or around very hot spots.

Oil may oxidize with the formation of small quantities of CO and CO₂, which can accumulate over long periods of time into more substantial amounts.

4.2 Decomposition of cellulosic insulation

The polymeric chains of solid cellulosic insulation (paper, pressboard, wood blocks) contain a large number of anhydroglucose rings, and weak C-O molecular bonds and glycosidic bonds which are thermally less stable than the hydrocarbon bonds in oil, and which decompose at lower temperatures. Significant rates of polymer chain scission occur at temperatures higher than 105 °C, with complete decomposition and carbonization above 300 °C. Mostly carbon monoxide and dioxide, as well as water, are formed, in much larger quantities than by oxidation of oil at the same temperature, together with minor amounts of hydrocarbon gases and furanic compounds. The latter can be analyzed according to IEC 61198, and used to complement DGA interpretation and confirm whether or not cellulosic insulation is involved in a fault. CO and CO₂ formation increases not only with temperature but also with the oxygen content of oil and the moisture content of paper.

4.3 Other sources of gas

Gases may be generated in some cases not as a result of faults in the equipment but through rusting or other chemical reactions involving steel, uncoated surfaces or protective paints.

Hydrogen may be produced by reaction of steel with water, as long as oxygen is available from the oil nearby. Large quantities of hydrogen have thus been reported in some transformers that had never been energized. Hydrogen may also be formed by reaction of free water with special coatings on metal surfaces, or by catalytic reaction of some types of stainless steel with oil, in particular oil containing dissolved oxygen at elevated temperatures. Hydrogen may also be formed in new stainless steel, absorbed during its manufacturing process, or produced by welding, and released slowly into the oil.

Hydrogen may also be formed by the decomposition of the thin oil film between overheated core laminates at temperatures of 140 °C and above (see [1]* of annex C).

Gases may also be produced by exposure of oil to sunlight or may be formed during repair of the equipment.

Internal transformer paints, such as alkyd resins and modified polyurethanes containing fatty acids in their formulation, may also form gases.

These occurrences, however, are very unusual, and can be detected by performing DGA analyses on new equipment which has never been energized, and by material compatibility tests. The presence of hydrogen with the total absence of other hydrocarbon gases, for example, may be an indication of such a problem.

NOTE – The case of gases formed at a previous fault and remnant in the transformer is dealt with in 5.3.

5 Identification of faults

Any gas formation in service, be it minimal, results from a stress of some kind, even if it is a very mild one, like normal temperature ageing. However, as long as gas formation is below typical values, it should not be considered as an indication of a "fault", but rather as "typical gas formation" (see figure 1).

5.1 Dissolved gas compositions

Although the formation of some gases is favoured, depending on the temperature reached or the energy contained in a fault (see 4.1), in practice mixtures of gases are almost always obtained. One reason is thermodynamic: although not favoured, secondary gases are still formed, albeit in minor quantities. Existing thermodynamic models derived from the petroleum industry, however, cannot predict accurately the gas compositions formed, because they correspond to ideal gas/temperature equilibria which do not exist in actual faults. Large temperature gradients also occur in practice, for instance as a result of oil flow or vaporization along a hot surface. This is particularly true in the case of arcs with power follow-through, which transfer a lot of heat to the oil vapour/decomposition gas layer between the arc and the oil, probably explaining the increasing formation of ethylene observed in addition to acetylene. In addition, existing thermodynamic models do not apply to paper, which turns irreversibly to carbon above 300 °C.

* Figures in square brackets refer to the bibliography in annex C.

5.2 Types of faults

Internal inspection of hundreds of faulty equipment has led to the following broad classes of visually detectable faults:

- partial discharges (PD) of the cold plasma (corona) type, resulting in possible X-wax deposition on paper insulation, or of the sparking type, inducing pinhole, carbonized perforations (punctures) in paper, which, however, may not be easy to find;
- discharges of low energy (D1), in oil or/and paper, evidenced by larger carbonized perforations through paper (punctures), carbonization of the paper surface (tracking) or carbon particles in oil (as in tap changer diverter operation);
- discharges of high energy (D2), in oil or/and paper, with power follow-through, evidenced by extensive destruction and carbonization of paper, metal fusion at the discharge extremities, extensive carbonization in oil and, in some cases, tripping of the equipment, confirming the large current follow-through;
- thermal faults, in oil or/and paper, below 300 °C if the paper has turned brownish (T1), and above 300 °C if it has carbonized (T2);
- thermal faults of temperatures above 700 °C (T3) if there is strong evidence of carbonization of the oil, metal coloration (800 °C) or metal fusion (>1 000 °C).

Table 1 – Abbreviations

PD	Partial discharges
D1	Discharges of low energy
D2	Discharges of high energy
T1	Thermal fault, $t < 300$ °C
T2	Thermal fault, 300 °C $< t < 700$ °C
T3	Thermal fault, $t > 700$ °C

5.3 Basic gas ratios

Each of the six broad classes of faults leads to a characteristic pattern of hydrocarbon gas composition, which can be translated into a DGA interpretation table, such as the one recommended in table 2 and based on the use of three basic gas ratios:

$$\frac{\text{C}_2\text{H}_2}{\text{C}_2\text{H}_4} \quad \frac{\text{CH}_4}{\text{H}_2} \quad \frac{\text{C}_2\text{H}_4}{\text{C}_2\text{H}_6}$$

Table 2 applies to all types of equipment, with a few differences in gas ratio limits depending on the specific type of equipment.

Table 2 – DGA interpretation table

Case	Characteristic fault	$\frac{C_2H_2}{C_2H_4}$	$\frac{CH_4}{H_2}$	$\frac{C_2H_4}{C_2H_6}$
PD	Partial discharges (see notes 3 and 4)	NS ¹⁾	<0,1	<0,2
D1	Discharges of low energy	>1	0,1 – 0,5	>1
D2	Discharges of high energy	0,6 – 2,5	0,1 – 1	>2
T1	Thermal fault $t < 300^\circ C$	NS ¹⁾	>1 but NS ¹⁾	<1
T2	Thermal fault $300^\circ C < t < 700^\circ C$	<0,1	>1	1 – 4
T3	Thermal fault $t > 700^\circ C$	<0,2 ²⁾	>1	>4

NOTE 1 – In some countries, the ratio C_2H_2/C_2H_6 is used, rather than the ratio CH_4/H_2 . Also in some countries, slightly different ratio limits are used.

NOTE 2 – The above ratios are significant and should be calculated only if at least one of the gases is at a concentration and a rate of gas increase above typical values (see clause 9).

NOTE 3 – $CH_4/H_2 < 0,2$ for partial discharges in instrument transformers.
 $CH_4/H_2 < 0,07$ for partial discharges in bushings.

NOTE 4 – Gas decomposition patterns similar to partial discharges have been reported as a result of the decomposition of thin oil film between overheated core laminates at temperatures of $140^\circ C$ and above (see 4.3 and [1] of annex C).

¹⁾ NS = Non-significant whatever the value.

²⁾ An increasing value of the amount of C_2H_2 may indicate that the hot spot temperature is higher than $1\,000^\circ C$.

Typical examples of faults in the various types of equipment (power transformers, instrument transformers, etc.), corresponding to the six cases of table 2, may be found in tables A.1, A.5, A.7 and A.11.

Some overlap between faults D1 and D2 is apparent in table 2, meaning that a dual attribution of D1 or D2 must be given in some cases of DGA results. The distinction between D1 and D2 has been kept, however, as the amount of energy in the discharge may significantly increase the potential damage to the equipment and necessitate different preventive measures.

NOTE – Combinations of gas ratios which fall outside the range limits of table 2 and do not correspond to a characteristic fault of this table may be considered a mixture of faults, or new faults which combine with a high background gas level (see 6.1).

In such a case, table 2 cannot provide a diagnosis, but the graphical representations given in annex B may be used to visualize which characteristic fault of table 2 is closest to the case.

The less detailed scheme of table 3 may also be used in such a case in order to get at least a rough distinction between partial discharges (PD), discharges (D) and thermal fault (T), rather than no diagnosis at all.

Table 3 – Simplified scheme of interpretation

Case	$\frac{\text{C}_2\text{H}_2}{\text{C}_2\text{H}_4}$	$\frac{\text{CH}_4}{\text{H}_2}$	$\frac{\text{C}_2\text{H}_4}{\text{C}_2\text{H}_6}$
PD		<0,2	
D	>0,2		
T	<0,2		

5.4 CO₂/CO ratio

The formation of CO₂ and CO from oil-impregnated paper insulation increases rapidly with temperature. Incremental (corrected) CO₂/CO ratios less than 3 are generally considered as an indication of probable paper involvement in a fault, with some degree of carbonization.

In order to get reliable CO₂/CO ratios in the equipment, CO₂ and CO values should be corrected (incremented) first for possible CO₂ absorption from atmospheric air, and for the CO₂ and CO background values (see 6.1 and clause 9), resulting from the ageing of cellulosic insulation, overheating of wooden blocks and the long term oxidation of oil (which will be strongly influenced by the availability of oxygen caused by specific equipment construction details and its way of operation).

Air-breathing equipment, for example, saturated with approximately 10 % of dissolved air, may contain up to 300 µl/l of CO₂ coming from the air. In sealed equipment, air is normally excluded but may enter through leaks, and CO₂ concentration will be in proportion of air present.

When excessive paper degradation is suspected (CO₂/CO < 3), it is advisable to ask for a furanic compounds analysis or a measurement of the degree of polymerization of paper samples, when this is possible.

5.5 O₂/N₂ ratio

Dissolved O₂ and N₂ may be found in oil, as a result of contact with atmospheric air in the conservator of air-breathing equipment, or through leaks in sealed equipment. At equilibrium, taking into account the relative solubilities of O₂ and N₂, the O₂/N₂ ratio in oil reflects air composition and is close to 0,5.

In service, this ratio may decrease as a result of oil oxidation and/or paper ageing, if O₂ is consumed more rapidly than it is replaced by diffusion. Factors such as the load and preservation system used may also affect the ratio, but ratios less than 0,3 are generally considered to indicate excessive consumption of oxygen.

5.6 C₂H₂/H₂ ratio

In power transformers, on load tap changer (OLTC) operations produce gases corresponding to discharges of low energy (D1). If some oil or gas communication is possible between the OLTC compartment and the main tank, or between the respective conservators, these gases may contaminate the oil in the main tank and lead to wrong diagnoses. The pattern of gas decomposition in the OLTC, however, is quite specific and different from that of regular D1s in the main tank.

C_2H_2/H_2 ratios higher than 2 to 3 in the main tank are thus considered as an indication of OLTC contamination. This can be confirmed by comparing DGA results in the main tank, in the OLTC and in the conservators. The values of the gas ratio and of the acetylene concentration depend on the number of OLTC operations and on the way the contamination has occurred (through the oil or the gas).

NOTE – If contamination by gases coming from the OLTC is suspected, interpretation of DGA results in the main tank should be done with caution by subtracting background contamination from the OLTC, or should be avoided as unreliable.

5.7 C_3 hydrocarbons

The interpretation method of gas analysis indicated above takes into account only C_1 and C_2 hydrocarbons. Some practical interpretation methods also use the concentrations of C_3 hydrocarbons, and their authors believe that they are liable to bring complementary information which is useful to make the diagnosis more precise. Because the C_3 hydrocarbons are very soluble in oil, their concentrations are practically not affected by a possible diffusion into ambient air. Conversely, and because they are very soluble, they are difficult to extract from the oil and the result of the analysis may greatly depend on the extraction method used. Moreover, experience has shown that, in most cases, a satisfactory diagnosis can be made without taking into account these hydrocarbons and for the sake of simplification, they have been omitted from the interpretation method indicated above.

5.8 Evolution of faults

Faults often start as incipient faults of low energy, which may develop into more serious ones of higher energies, leading to possible gas alarms, breakdowns and failures.

When a fault is detected at an early stage of development, it may be quite informative to examine not only the increase in gas concentrations, but also the possible evolution with time toward a more dangerous high-energy fault of the final stage type.

For example, some current transformers have operated satisfactorily for long periods of time with very high levels of hydrogen produced by partial discharges. However, partial discharges may also cause the formation of X-wax. When the X-wax is present in sufficient quantity to increase the dissipation losses in the paper-oil insulation, a thermal fault may occur, eventually leading to catastrophic thermal runaway and breakdown.

In other occurrences, however, instant final breakdown may occur without warning.

5.9 Graphical representations

Graphical representations of gas ratios are convenient to follow this evolution of faults visually. Annex B gives examples of graphical representation of faults.

These representations are also useful in cases which do not receive a diagnosis using table 2, because they fall outside the gas ratios limits. Using figures B.1 or B.2, the zone or box which is closest to such an undiagnosed case can be easily visualized and attributed with caution to this case. Figure B.3 is particularly useful since it always provide a diagnosis in such cases.

6 Conditions for calculating ratios

6.1 Examination of DGA values

DGA sampling and analysis should be done in accordance with the recommendations of IEC 60567.

- a) Values of 0 $\mu\text{l/l}$ on a DGA report or below the analytical detection limits S shall be replaced by "below the S value for this gas" (see IEC 60567 for recommended S values)
- b) If successive DGA analyses have been performed over a relatively short period of time (days or weeks), inconsistent variations (e.g. brutal decreases of concentrations) may have to be eliminated as an indication of a sampling or analytical problem.
- c) Gas ratios are significant and should be calculated only if at least one gas concentration value is above typical value and above typical rate of gas increase (see note 2 of table 2 and clause 9).
- d) If gas ratios are different from those for the previous analysis, a new fault may superimpose itself on an old one or normal ageing. In order to get only the gas ratios corresponding to the new fault, subtract the previous DGA values from the last ones and recalculate ratios. This is particularly true in the case of CO and CO₂ (see 5.4). Be sure to compare DGA values of samples taken at the same place and preferably in moving oil. Interpretation should also take into account treatments previously made on the equipment, such as repair, oil degassing or filtering, which may affect the level of gases in the oil.

NOTE – In the case of air-breathing power transformers, losses occur very slowly with time by diffusion through the conservator or as a result of oil expansion/temperature cycles, with the result that the measured gas levels may be slightly less than the gas levels actually formed in the transformer. However, there is no agreement concerning the magnitude of this diffusion loss in service, some considering it as totally negligible, others as potentially significant, depending on the type of equipment used. In case of doubt, it may be expedient to measure the gas concentration in the conservator to get an idea of the volume ventilated. Significant diffusion losses may affect gas ratios, typical values of gas concentrations and of rates of gas increase.

6.2 Uncertainty on gas ratios

Because of the precision on DGA values, there is also an uncertainty on gas ratios, which can be calculated using the precision on DGA values described in IEC 60567.

Above $10 \times S$ (S being the analytical detection limit), the precision is typically 5 % on DGA values and up to 10 % on a gas ratio. Below $10 \times S$, the precision on DGA values decreases rapidly, to typically 20 % at $5 \times S$ and up to 40 % on a gas ratio.

Caution should therefore be exercised when calculating gas ratios at low gas levels (lower than $10 \times S$), keeping in mind the possible variations resulting from the reduced precision. This is particularly true for instrument transformers and bushings, where typical values of gas concentration may be below $10 \times S$.

7 Application to free gases in gas relays

During a fault, the production rate of gases of all types is closely linked to the rate of energy liberation. Thus, the low rate of energy liberation in partial discharges, or in a low-temperature hot spot, will cause gases to evolve slowly and there is every probability that all the gas produced will dissolve in the oil. The higher rate of energy liberation of a high-temperature core fault, for example, can cause an evolution of gas rapid enough to result in gas bubbles. These will usually partially dissolve in the oil (and exchange with gases already dissolved) but some gas may well reach the gas collecting relay or gas cushion; this gas may approach equilibrium with the gases dissolved in the oil.

A very high rate of energy liberation associated with a power arcing fault causes a rapid and substantial evolution of gas (the resulting pressure surge normally operates the surge element of the gas collecting relay). The large gas bubbles rise quickly to the relay and exchange little gas with the oil so that the gas that collects in the relay is initially far from being in equilibrium with the gases dissolved in the oil. However, if this gas is left for a long time in the relay, some constituents will dissolve, modifying the composition of the gas collected. Acetylene, which is produced in significant quantities by an arcing fault and which is very soluble, is a noteworthy example of a gas which may dissolve comparatively quickly to produce misleading results.

In principle, the analysis of free gases from a gas collecting relay or from a gas cushion may be evaluated in the same way as the analysis of gases dissolved in the oil. However, where the surge element has operated and gas has accumulated in substantial quantities, there is a possibility of having a serious fault, and analyses of the gases should be undertaken to identify the fault. Buchholz alarms due to air accumulation are also possible following a combination of warm days and sudden temperature drops at night.

It is therefore important to collect the gas at the relay as soon as possible without burning it, and sample the oil in the relay and in the main tank.

Where gas has accumulated slowly, assessment of the gases dissolved in the oil is more informative than that of the free gases; this gas-in-oil analysis is also essential in order to determine the total rate of evolution of gases and thus check whether the fault is growing, which is the most important matter to investigate. When analysis of free gases is undertaken, it is necessary to convert the concentrations of the various gases in the free state into equivalent concentrations in the dissolved state, using table 4, before applying the gas ratio method of table 2, and to compare them to the dissolved gas concentrations in the oil of the relay and the main tank.

Applying the principles set out above, comparison of the actual concentrations in the oil with the equivalent concentrations in the free gas may give valuable information on how far gas bubbles may have risen through the oil and, hence, on the rate of gas evolution.

The calculation of dissolved gas concentrations equivalent to free gas concentrations is made by applying the Ostwald coefficient for each gas separately. For a particular gas, the Ostwald coefficient k is defined as follows:

$$k = \frac{\text{concentration of gas in liquid phase}}{\text{concentration of gas in gas phase}}$$

with concentrations in microlitres per litre.

The Ostwald coefficients for various gases in mineral insulating oils at 20 °C and 50 °C are given in table 4.

Table 4 – Ostwald coefficients for various gases in mineral insulating oils

Gas	<i>k</i> at 20 °C	<i>k</i> at 50 °C
N ₂	0,09	0,09
O ₂	0,17	0,17
H ₂	0,05	0,05
CO	0,12	0,12
CO ₂	1,08	1,00
CH ₄	0,43	0,40
C ₂ H ₆	2,40	1,80
C ₂ H ₄	1,70	1,40
C ₂ H ₂	1,20	0,9

NOTE – Data given in this table represent mean values obtained on some of the current types of transformer mineral insulating oils. Actual data may differ a little from these figures. Nevertheless, data given above may be used without influencing conclusions drawn from recalculated test results.

The Ostwald coefficient is independent of the actual partial pressures of the gas concerned. The gas and liquid phases are assumed to be at the same temperature; this is rarely the case but the error introduced by any difference will not invalidate the conclusions reached.

8 Gas concentration levels in service

8.1 Probability of failure in service

8.1.1 General

The probability or risk of having an incident or a failure in service is related to gas concentration levels.

Below certain concentration levels (quoted as typical values or normal values), the probability of having a failure is low. The equipment is considered healthy, although a failure cannot be totally ruled out, even at these low levels, but it is improbable. A first rough screening between healthy and suspect analyses can therefore be obtained by calculating typical values for the equipment.

The probability of having a failure may increase significantly at values much above typical concentration levels. The situation is then considered critical, for even though a failure may never occur at these high levels, the risk of having one is high. Such failures may be divided into two categories:

- failures that develop within a very short time (which are therefore impossible to detect by oil sampling/laboratory analysis, but only by on-line detectors);
- failures developing over an extended time span. Only this second category may be detected by DGA laboratory analysis.

8.1.2 Calculation methods

Utilities with large DGA and equipment maintenance databases are able to calculate the probability of failure in service for a given type of equipment and at a given concentration level of a gas. This can be obtained by calculating the number of DGA analyses which have led to an actual failure or incident in service (gas alarm, failure, repair, outage, etc.), and comparing it to the total number of DGA analyses on this type of equipment and at this gas concentration level.

A large number of analyses is necessary to get reliable values of failure probability. Knowledge of these values, however, is useful when choosing the normality percentage most appropriate for a given network and type of equipment (see 8.2.3).

8.2 Typical concentration values

8.2.1 General

Typical concentration values are the acceptable gas quantities below which field experience shows no detectable or possible incipient fault, and which are overpassed by only an arbitrarily low percentage of higher gas contents, for example 10 %. Typical concentration values will be referred to in such an example as the 90 % typical values.

However, typical concentration values are preferably to be considered as initial guidelines for decision making, when no other experience is available. They shall not be used to ascertain whether or not a fault exists within an equipment. They should be viewed as values above which the rate of gas formation may permit the detection of a probable fault.

Typical concentration values are affected by a number of factors, chiefly the operating time since commissioning, the type of equipment and the nature of the fault (electrical or thermal). For power transformers, the type of oil protection, load factor and operation mode are other influencing factors.

Typical concentration values may be calculated as follows and should be obtained by the equipment users on the specific types of equipment.

8.2.2 Calculation methods

The simplest method of calculation consists in gathering all the DGA results concerning a specific type of equipment. For each characteristic gas considered, the cumulative number of DGA analyses where the gas concentration is below a given value is calculated, then plotted as a function of gas concentration. Using the plotted curve, the gas concentration corresponding to a given percentage of the total cumulative number of analyses (for instance 90 %) is the 90 % typical concentration value for that gas and type of equipment.

8.2.3 Choice of normality percentages

If the normality percentage chosen (e.g. 90 %, 95 % or other) is too low, suspicion will be placed on too many pieces of equipment, with a loss of credibility in the diagnosis and recommendations, and an increase in maintenance costs. If the normality percentage is chosen too high, failure may occur without advance warning, also involving considerable costs.

The choice of a normality percentage is often an educated guess, left to the experience of the user of similar equipment. A certain amount of leeway in the choice of a normality percentage is also provided by considering the probability of failure and the actual failure rate of the equipment in service. In the absence of such information or experience, users may choose conservative normality percentages such as 90 % as a rough screening value. If adequate databases are not available to calculate typical values, users may also adopt as a first step, values observed on other networks and indicated in the application notes. It is apparent from these values that, in general, typical values are lower in instrument transformers and bushings than in power transformers, especially those with a communicating OLTC.

8.3 Alarm concentration values

Alarm concentration values are those values of concentration above which the probability of an incident is sufficiently high to require urgent competent decisions and/or actions.

Alarm concentration values should be set by users, manufacturers or independent experts, based on previous experience with equipment with similar characteristics (voltage, type, manufacturer, loading practices, age, etc.).

8.4 Rates of gas increase

If there is no increase in gas concentration over the last analysis, chances are that the fault has disappeared (or that a very small one is still there, in the case of air-breathing equipment, compensated by diffusion losses through the conservator, see 6.1).

What should be considered as a typical or alarm rate of gas increase depends very much on equipment type and age, type of identified faults, air-breathing and load patterns, and volume of the insulation involved. Ultimately the rate of increase should be decided by the user of the equipment, the manufacturer and/or other experts.

An increase in gas concentrations of more than 10 % per month above typical concentration values is generally considered a prerequisite for pronouncing the fault as active, provided it is clear that the precision on DGA values is better than 10 % after one month. Much higher rates of gas increase, such as 50 % per week, and/or evolving towards faults of higher energy (e.g. D2 or T3), are generally considered very serious, especially if they exceed alarm concentration values. In the case of power transformers, typical rates of gas production in millilitres per day are also reported (see table A.3). Special attention should be given to cases where there is an acceleration in the rate of gas increase.

NOTE – In the case of carbon oxides, rates of gas increase are dependent on the oil-to-paper ratio, which may be quite different depending on the equipment considered.

On-line gas detectors, including those already available for hydrogen, may be particularly well-suited for detecting non-typical rates of gas increase occurring within minutes, hours or weeks, which is generally not possible with routine oil samplings done at monthly or yearly intervals. However, when such increases are detected by a gas detector, complete DGA analyses shall be made at the laboratory to confirm the detector readings, evaluate the rates of increase of the various gases and identify the fault.

9 Recommended method of DGA interpretation (figure 1)

a) Reject or correct inconsistent DGA values (see 6.1). Calculate the rate of gas increase since the last analysis, taking into account the precision on DGA results.

If all gases are below typical values of gas concentrations and rates of gas increase, report as "Normal DGA/healthy equipment".

If at least one gas is above typical values of gas concentrations and rates of gas increase, calculate gas ratios and identify fault using table 2 (see 5.3). Check for eventual erroneous diagnosis (see 4.3).

If necessary subtract last values from present ones before calculating ratios, particularly in the case of CO, CO₂ (see 6.1).

If DGA values are above typical values but below $10 \times S$ (S = analytical detection limit), see 6.2.

b) Determine if gas concentrations and rates of gas increase are above alarm values. Verify if fault is evolving towards final stage (see 5.8). Determine if paper is involved (see 4.2 and 5.4).

c) Take proper action according to best engineering judgment and/or with the help of figure 1.

It is recommended to

- 1) increase sampling frequency (quarterly, monthly or other) when the gas concentrations and their rates of increase exceed typical values;
- 2) consider immediate action when gas concentrations and rates of gas increase exceed alarm values.

10 Report of results

NOTE – The report should be adapted to the specific type of equipment considered.

The DGA interpretation report should include the following, when available:

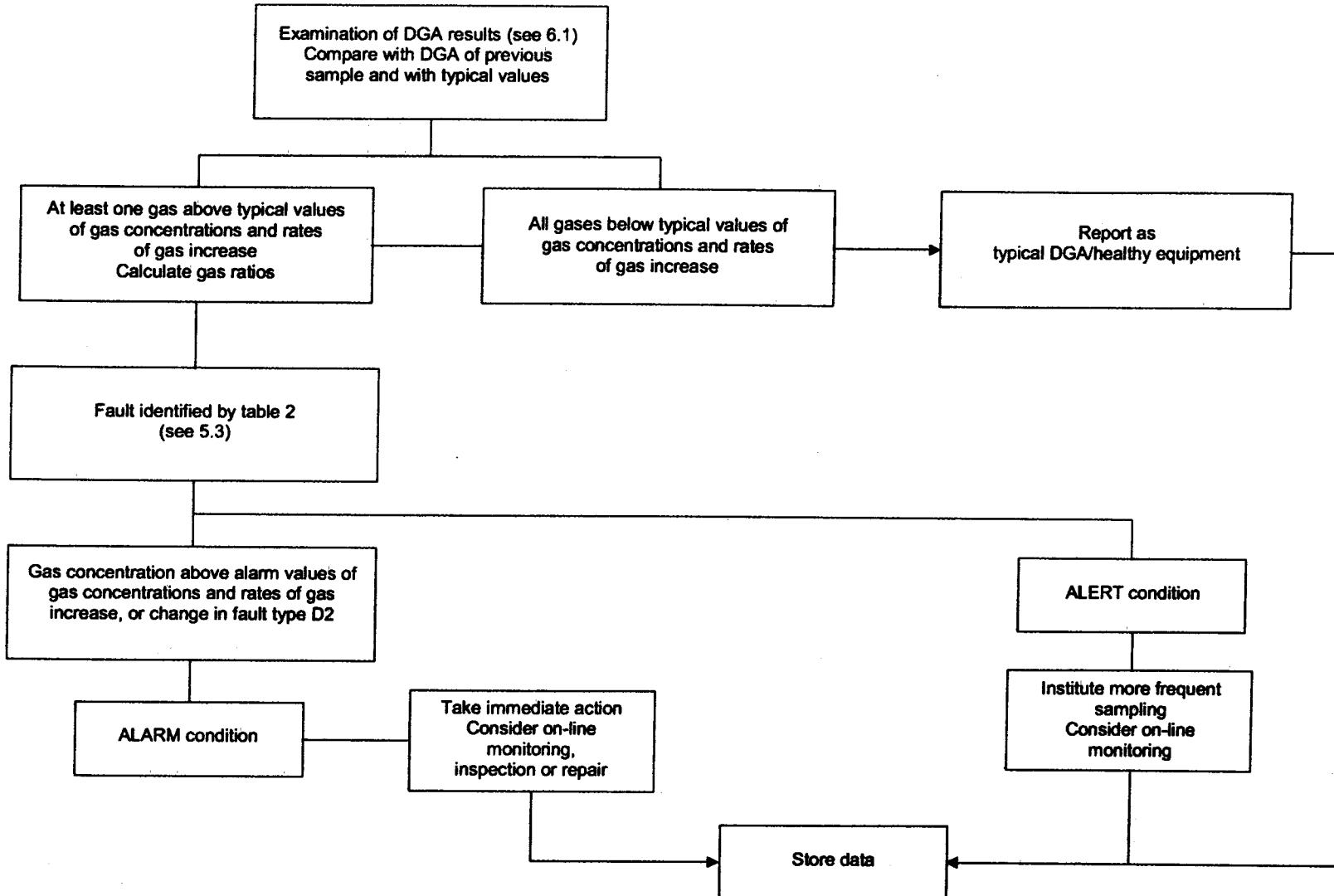
a) DGA analysis report, including S values, method of DGA analysis, and date of analysis.

NOTE – Values of 0 $\mu\text{l/l}$ on a DGA report or below the S values are replaced by "below the S value for this gas".

b) specific information on the equipment such as:

- 1) date of commissioning, voltage, general type (e.g. power or instrument transformer), rated power;
- 2) special features (e.g. sealed or air-breathing, type of OLTC (see A.1.6));
- 3) oil volume;
- 4) oil or gas sampling date;
- 5) oil or gas sampling location;

- c) special operations or incidents just before and after the oil or gas sampling, such as tripping, gas alarm, degassing, repair, outage;
- d) previous DGA on the equipment;
- e) indication of typical values for this specific equipment, if known;
- f) indication of "Typical DGA/healthy equipment" or "Fault";
- g) in case of "Fault", identification of the fault using table 2 (see 5.3), with values of the calculated gas ratios indicated;
- h) indication of paper involvement or not, with value of the CO_2/CO ratio;
- i) recommended actions:
 - 1) new frequency of oil sampling,
 - 2) furanic compound analysis if CO_2/CO ratio is lower than 3,
 - 3) other tests.



NOTE – For power transformers, see also A.1.5.

Figure 1 – Flow chart

Annex A
(informative)

Equipment application notes

WARNING: Typical concentration values given in these application notes are average values for various types of equipment. They only provide indications on the ranges of values usually observed in the equipment.

Individual users may get different typical values, depending on their specific equipment, manufacturing designs and load practices. They are urged to calculate their own values, following methods outlined in clause 8.

The values indicated in the present application notes should be consulted only in the absence of more precise in-house data from the user and should never be used in a contract without a special agreement between the parties. Thorough engineering judgment should be exercised in all cases.

The typical concentration values given in the tables are not limiting values. If the values are exceeded it is an indication that further routine DGA analyses should be undertaken with shorter intervals between samples to monitor any trends in the increase of gas produced and to provide further diagnostic information.

A.1 Power transformers

Values given in clause A.1 have been proposed by IEC technical committee 10. They will be reviewed by a Joint Working Group between IEC technical committees 10 and 14: Power transformers.

A.1.1 Specific sub-types

- air-breathing (open conservator type);
- sealed or nitrogen-blanketed;
- inter-tie transmission versus generation step-up;
- no OLTC communicating with main tank versus communicating OLTC;
- core-type or shell-type;
- reactors.

A.1.2 Typical faults

See table A.1.

Table A.1 – Typical faults in power transformers

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from incomplete impregnation, high-humidity in paper, oil supersaturation or cavitation, and leading to X-wax formation
D1	Discharges of low energy	Sparking or arcing between bad connections of different or floating potential, from shielding rings, toroids, adjacent disks or conductors of winding, broken brazing or closed loops in the core Discharges between clamping parts, bushing and tank, high voltage and ground within windings, on tank walls Tracking in wooden blocks, glue of insulating beam, winding spacers. Breakdown of oil, selector breaking current
D2	Discharges of high energy	Flashover, tracking, or arcing of high local energy or with power follow-through Short circuits between low voltage and ground, connectors, windings, bushings and tank, copper bus and tank, windings and core, in oil duct, turret. Closed loops between two adjacent conductors around the main magnetic flux, insulated bolts of core, metal rings holding core legs
T1	Thermal fault $t < 300^\circ\text{C}$	Overloading of the transformer in emergency situations Blocked item restricting oil flow in windings Stray flux in damping beams of yokes
T2	Thermal fault $300^\circ\text{C} < t < 700^\circ\text{C}$	Defective contacts between bolted connections (particularly between aluminium busbar), gliding contacts, contacts within selector switch (pyrolytic carbon formation), connections from cable and draw-rod of bushings Circulating currents between yoke clamps and bolts, clamps and laminations, in ground wiring, defective welds or clamps in magnetic shields Abraded insulation between adjacent parallel conductors in windings
T3	Thermal fault $t > 700^\circ\text{C}$	Large circulating currents in tank and core Minor currents in tank walls created by a high uncompensated magnetic field Shorting links in core steel laminations

A.1.3 Identification of faults by DGA

Table 2 (see 5.3) applies directly to all transformer sub-types, except those equipped with a communicating OLTC. In the latter cases, if $\text{C}_2\text{H}_2/\text{H}_2$ is higher than 2 to 3, there is contamination from the OLTC into the main tank, and table 2 does not apply or applies with care, after subtracting background contamination from the OLTC (see 5.6).

NOTE 1 – Any gas formation below typical values of gas concentration and rates of gas increase should not be considered as an indication of "fault", but rather as "normal gas formation". Ratios are not significant in such a case (see note 2 of table 2).

NOTE 2 – In the case of air-breathing power transformers, losses of gas occur very slowly with time by diffusion through the conservator or as a result of oil expansion cycles, with the result that the measured gas levels may be slightly less than the gas levels actually formed in the transformer. However, there is no agreement concerning the magnitude of this diffusion loss in service, some considering it as totally negligible, others as potentially significant, depending on the type of equipment considered. In case of doubt, to get an idea of the volume ventilated it may be expedient to measure the gas concentration in the conservator as well. Significant diffusion losses may affect gas ratios, typical values of gas concentrations and rates of gas increase (see 6.1).

A.1.4 Typical concentration values

Ranges of 90 % typical values observed in power transformers, from more than 15 individual networks worldwide and including more than 15 000 transformers, are given in table A.2.

These levels are influenced mostly by equipment sub-type, fault type and age. Typical values, for example, are usually higher in sealed transformers than in air-breathing transformers of the same type. All types of influence factors and sub-types given in A.1.1 are included in table A.2.

The 90 % normality percentage is the most frequently used. However, this percentage depends on the characteristics of the transformer population.

The values given in table A.2 are for information only.

Table A.2 – Ranges of 90 % typical concentration values observed in power transformers (all types)

Transformer sub-type	H ₂	CO	CO ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	Values in microlitres per litre
No OLTC	60-150	540-900	5 100-13 000	40-110	50-90	60-280	3-50	
Communicating OLTC	75-150	400-850	5 300-12 000	35-130	50-70	110-250	80-270	

NOTE 1 – The values listed in this table were obtained from individual networks. Values on other networks may differ.

NOTE 2 – "Communicating OLTC" means that some oil and/or gas communication is possible between the OLTC compartment and the main tank or between the respective conservators. These gases may contaminate the oil in the main tank and affect the normal values in these types of equipment. "No OLTC" refers to transformers not equipped with an OLTC, or equipped with an OLTC not communicating with or leaking to the main tank.

NOTE 3 – In some countries, typical values as low as 0,5 µl/l for C₂H₂ and 10 µl/l for C₂H₄ have been reported.

A.1.5 Typical rates of gas increase

Rates of gas increase in millilitres per day, as compared to rates of gas concentration increase in percent per month (see 8.4), are believed to be more closely related to the size and severity of the fault, and not to be affected by the oil volume of the transformer.

However, these rates necessitate knowledge of the oil volume, which is not always possible.

What should be considered as typical rates of gas increase depends very much on equipment type and age, type of the identified faults, air-breathing and load patterns, and the volume of insulation involved. They should be ultimately decided by the user of the equipment, the manufacturer and/or other experts.

Experience has shown that the rates in table A.3 indicate a typical behaviour of air-breathing equipment.

The values given in table A.3 are for information only.

Table A.3 – Typical rates of gas increase for power transformers

Values in millilitres per day	
Hydrogen	<5
Methane	<2
Ethane	<2
Ethylene	<2
Acetylene	<0,1
Carbon monoxide	<50
Carbon dioxide	<200

NOTE – The values listed in this table were obtained from individual networks. Values on other networks may differ. Values on other types of transformers, for instance sealed transformers, may also differ.

Equation to calculate the rate of gas increase:

$$\text{rate} = \frac{(y_2 - y_1) m}{\rho (d_2 - d_1)} \text{ ml/day}$$

where

y_1 is the reference analysis;

y_2 is the last analysis;

$(y_2 - y_1)$ is the increase, in microlitre per litre;

m is the mass of oil, in kilograms;

ρ is the mass density, in kilograms per cubic metre;

d_1 is the date for y_1 ;

d_2 is the date for y_2 .

NOTE – Some users prefer typical rates of gas increase expressed in microlitres per litre per month or in per cent per month.

A.1.6 Specific information to be added to the DGA report (see clause 10)

- power rating;
- transformer sub-type: air-breathing or sealed;
- top oil temperature;
- type of cooling system: ONAN (oil natural air natural), OFAF (oil forced air forced), etc.;
- hours of service;
- type of OLTC (communicating with the main tank or not);
- number of OLTC operations, if known.

NOTE – OLTCs are often composed of a selector switch, located in the oil of the main tank, and of a diverter switch, located in a separate tank but on the same operating axle.

A.2 Industrial and special transformers

A.2.1 Specific sub-types

- furnace transformers;
- rectifier transformers;
- railway transformers;
- distribution transformers (only industrial and service transformers, below 10 MVA, not from utilities);

A.2.2 Typical faults

See table A.1.

A.2.3 Identification of faults

See A.1.3.

A.2.4 Typical concentration values

See table A.4.

The values given in table A.4 are for information only.

Table A.4 – Examples of 90 % typical concentration values observed on a typical network (all types of transformers)

Transformer sub-type	H ₂	CO	CO ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	Values in microlitres per litre	
Furnace *	200	800	6 000	150	150	200	*		
	100	200	5 000	50	50	50	5		
NOTE – The values listed in this table were obtained from one particular network. Values on other networks may differ.									
* The data are influenced by the design and assembly of the on-load tap changer. For this reason, no statistically significant value can be proposed for acetylene.									

A.3 Instrument transformers

A.3.1 Specific sub-types

CT: Current transformers (eyebolt or hairpin design)
VT: Voltage transformers
CTCV: Combined transformers (current-voltage)
CIVT: Cascade (inductive) voltage transformers
CVT: Capacitor voltage transformers
MVT: Magnetic voltage transformers (see [2] of annex C).

NOTE – Definitions of these specific sub-types can be found in [6] of annex C.

A.3.2 Typical faults

See table A.5.

Failure rates have been reported as being about 1 % of the total population (see [2] of annex C), although much higher rates were observed on a limited number of sub-groups.

The most frequent final failures involve local or catastrophic dielectric breakdown of paper insulation, following lengthy partial discharge activity and/or thermal runaways.

Table A.5 – Typical faults in instrument transformers

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from poor impregnation, humidity in paper, oil supersaturation, pockers or folds in paper, leading to X-wax deposition and increased dielectric losses Discharges related to switching operations from a nearby substation bus system (in the case of CTs) or to overvoltages at the edges of capacitor unit sections (case of CVTs)
D1	Discharges of low energy	Sparking around loose connections or floating metal strips Tracking in paper Arcing in static shielding connections
D2	Discharges of high energy	Local short circuits between capacitive stress grading foils, with high local current densities able to melt down foils General short circuits with power follow-through are often destructive, resulting in equipment breakage or explosion, and a DGA is not always possible after failure
T2	Thermal fault $300^{\circ}\text{C} < t < 700^{\circ}\text{C}$	Circulating currents in paper insulation resulting from high dielectric losses, related to X-wax contamination, moisture or incorrect selection of insulating materials, and resulting in dielectric heating and thermal runaways Bad contacts in connections or welds Overheating due to the ferroresonant circuit in MVTs
T3	Thermal fault $t > 700^{\circ}\text{C}$	Circulating currents on steel lamination edges

A.3.3 Identification of faults by DGA

Table 2 (see 5.3) applies to all sub-types, with CH_4/H_2 lower than 0,2 instead of lower than 0,1 for partial discharges.

A.3.4 Typical concentration values

Ranges of 90 % typical values observed in instrument transformers are given in table A.6. The 90 % normality percentage is the most frequently used. Factors of influence are equipment sub-type, fault type, and age.

The values given in table A.6 are for information only.

Table A.6 – Ranges of 90 % typical concentration values observed in instrument transformers

Transformer sub-type	H ₂	CO	CO ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂	Values in microlitres per litre
CT	6-300	250-1100	800-4 000	11-120	7-130	3-40	1-5	
VT	70-1000					20-30	4-16	

NOTE 1 – The values listed in this table were obtained from one particular network. Values on other networks may differ.

NOTE 2 – The value for H₂ in CTs is much lower for rubber sealings ($\pm 20 \mu\text{l/l}$) than for metal sealings ($\pm 300 \mu\text{l/l}$).

The following maximum admissible values for sealed instrument transformers without any action to be taken on the transformer have been proposed

Values in microlitres per litre

H ₂	CO	CO ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂
300	300	900	30	50	10	2

A.4 Bushings

A.4.1 Specific sub-types

- condenser type;
- non-condenser type.

A.4.2 Typical faults

See table A.7

In a number of instances, partial discharges result in increased dielectric losses, thermal runaway and final breakdown.

Most frequent final failures are related to the breakdown of core insulation between short-circuited layers (as a result of partial discharges or thermal runaway), flashovers along the internal surface of the porcelain (often resulting in explosions) and flashovers along the core surface.

Table A.7 – Typical faults in bushings

Type	Fault	Examples
PD	Partial discharges	Discharges in gas-filled cavities resulting from humidity in paper, poor impregnation, oil supersaturation or contamination, or X-wax deposition. Also in loose insulating paper displaced during transportation with pockers or folds in paper
D1	Discharges of low energy	Sparking around loose connections at capacitive tap Arcing in static shielding connections Tracking in paper
D2	Discharges of high energy	Localized short-circuits between capacitive stress grading foils, with high local current densities able to melt down foils (see definition of D2 in 5.2), but not leading to the explosion of the bushing
T2	Thermal fault $300^{\circ}\text{C} < t < 700^{\circ}\text{C}$	Circulating currents in paper insulation resulting from high dielectric losses, related to contamination or improper selection of insulating materials, and resulting in thermal runaways Circulating currents in poor connections at bushing shield or high voltage lead, with the temperature transmitted inside the bushing through conduction by the conductor

A.4.3 Identification of faults by DGA

A simplified table of interpretation is proposed.

Table A.8 – Simplified interpretation scheme for bushings

Fault	$\frac{\text{C}_2\text{H}_2}{\text{C}_2\text{H}_4}$	$\frac{\text{CH}_4}{\text{H}_2}$	$\frac{\text{C}_2\text{H}_4}{\text{C}_2\text{H}_6}$	$\frac{\text{CO}_2}{\text{CO}}$
PD		<0,07		
D	>1			
T			>1	
TP				<1, >20

NOTE – PD = partial discharges
D = discharges
T = thermal fault
TP = thermal fault in paper

In cases where a single characteristic fault cannot be attributed using this simplified table, or when a more precise diagnosis is required, the general table 2 should be used.

NOTE – Some modern bushings contain mixtures of mineral oil and dodecylbenzene (DDB), in proportions not known. Gas compositions evolved from DDB are not the same as from mineral oil, and DDB absorbs more gas than mineral oil.

A.4.4 Typical concentration values

The following 95 % typical values are proposed.

The values given in table A.9 are for information only.

Table A.9 – 95 % typical concentration values in bushings

Values in microlitres per litre

H_2	CO	CO_2	CH_4	C_2H_6	C_2H_4	C_2H_2
140	1 000	3 400	40	70	30	2

A.5 Oil-filled cables

A.5.1 Typical faults

Discharges and hot spots at cable terminations or junctions.

A.5.2 Identification of faults

Table 2 applies.

DGA is difficult to apply in cables due to the lack of representativity of oil samples (sampling sometimes possible only a long distance from the fault; lack of oil convection; gas trapped in paper insulation ...).

Also, modern cables often contain mixtures of mineral oil and dodecylbenzene (DDB), in proportions not known. Gas compositions evolved from DDB are not the same as from mineral oil, and DDB absorbs more gas than mineral oil under electric stress.

A.5.3 Typical concentration values

The values given in table A.10 are for information only.

The following 95 % typical concentration values have been observed on cables.

Table A.10 – Ranges of 95 % typical concentration values observed on cables

Values in microlitres per litre

H ₂	CO	CO ₂	CH ₄	C ₂ H ₆	C ₂ H ₄	C ₂ H ₂
150-500	40-100	220-500	5-30	10-25	3-20	2-10

NOTE – These values are examples taken from one particular network. Values on other networks and with different types of cable designs may differ.

A.6 Switching equipment

A.6.1 Specific sub-types

- tap changers (OLTC);
- selector switches;
- switchgear.

A.6.2 Typical faults

See table A.11.

Table A.11 – Typical faults in switching equipment

Type	Fault	Examples
D1	Discharges of low energy	Normal operation of OLTC, selectors Arcing on off-load selector switch ring, OLTC connections
D2	Discharges of high energy	Switch contacts do not reach their final position but stop halfway, due to a failure of the rotating mechanism, inducing a sparkover discharge Arcing on off-load selector switch ring, OLTC connections, of high energy or with power follow-through, with failure often transmitted to transformer windings
T3	Thermal fault	Increased resistance between contacts of OLTC or change-over selector, as a result of pyrolytic carbon growth, selector deficiency or a very large number of operations

NOTE 1 – In this table are given examples of faults detected by DGA of oil samples taken from the switching compartment.

NOTE 2 – Switching equipment attached to transformers is complex and of various designs. The detailed description of these systems and the interpretation of DGA results should be made with the help of the switching equipment manufacturer, particularly concerning the types of discharges which can or cannot occur in this equipment.

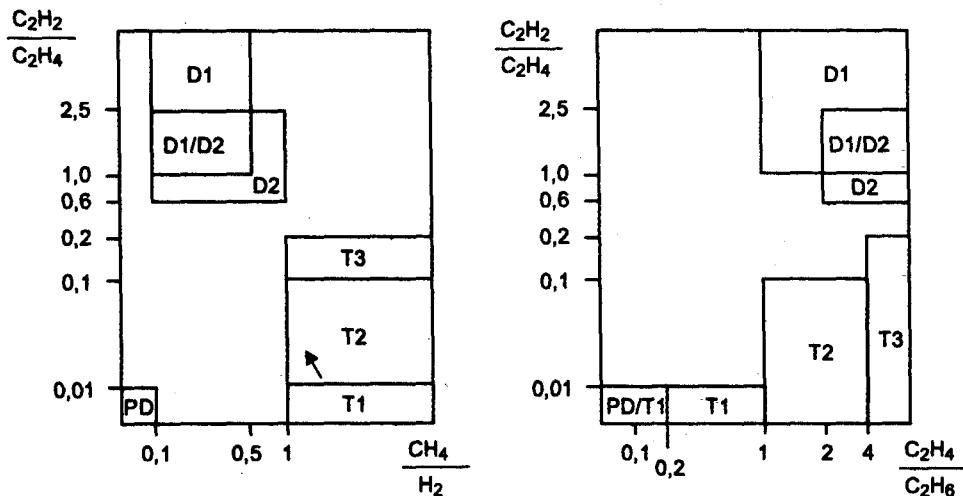
A.6.3 Identification of faults by DGA

Table 2 applies to all sub-types.

As the number of OLTC operations increases, a thermal effect has been observed to superimpose over the pure discharge effect of breaking current, possibly as a result of the increase in resistance of OLTC contacts contaminated by pyrolytic carbon.

Annex B
(informative)

Graphical representation of gas ratios (see 5.9)

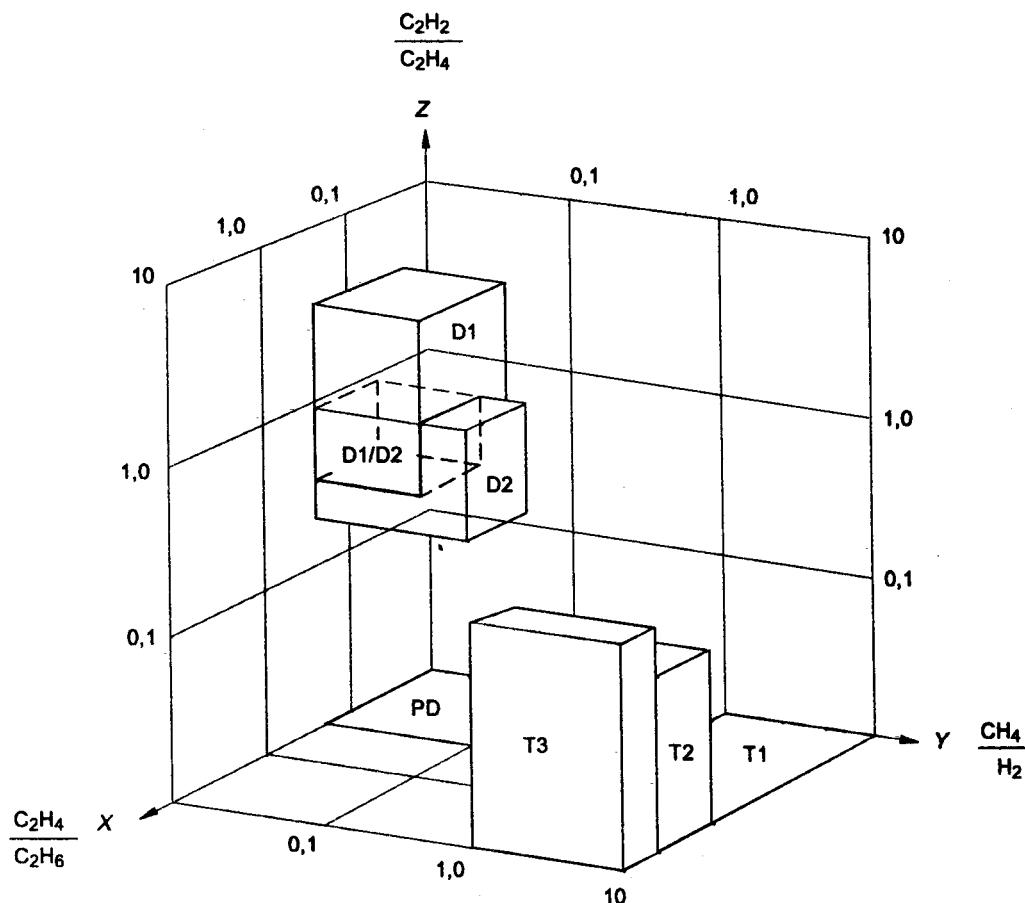


Key	PD	Partial discharges
D1		Discharges of low energy
D2		Discharges of high energy
T1		Thermal fault, $t < 300$ °C
T2		Thermal fault, 300 °C $< t < 700$ °C
T3		Thermal fault, $t > 700$ °C

NOTE 1 – The arrow indicates increasing temperature.

NOTE 2 – The axes are limited to values of 10 for clarity of presentation, but actually extend to unlimited values. The coordinates of each zone are the same as in table 2 and figure B.2.

Figure B.1 – Graphical representation 1 of gas ratios (see [3] of annex C)

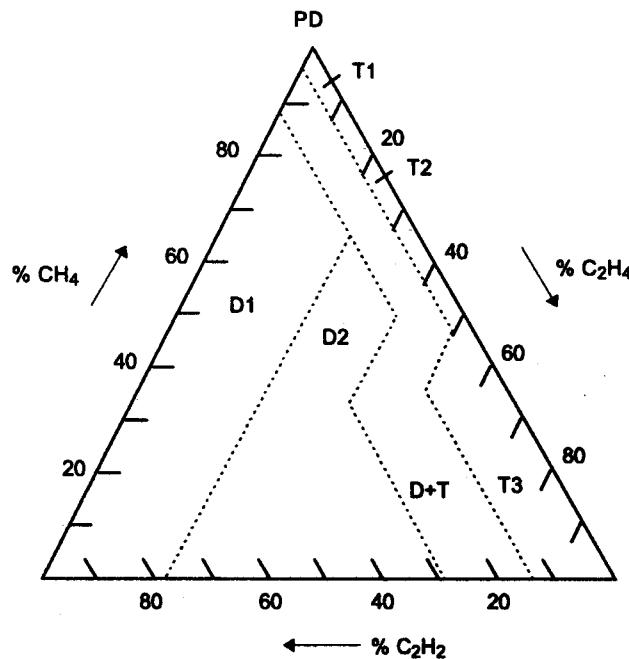


Key	PD	Partial discharges
	D1	Discharges of low energy
	D2	Discharges of high energy
	T1	Thermal fault, $t < 300^\circ C$
	T2	Thermal fault, $300^\circ C < t < 700^\circ C$
	T3	Thermal fault, $t > 700^\circ C$

NOTE 1 – Each of the cases defined in table 2 is represented by a volume or "box" on the 3-D graphic.

NOTE 2 – The coordinates of each box are the same as in figure B.1 and table 2. It is more convenient to use this representation with the help of a computer software package.

Figure B.2 – Graphical representation 2 of gas ratios (see [4] of annex C)



where

$$\% \text{C}_2\text{H}_2 = \frac{100x}{x+y+z} \quad \text{for } x = [\text{C}_2\text{H}_2] \text{ in microlitres per litre}$$

$$\% \text{C}_2\text{H}_4 = \frac{100y}{x+y+z} \quad \text{for } y = [\text{C}_2\text{H}_4] \text{ in microlitres per litre}$$

$$\% \text{CH}_4 = \frac{100z}{x+y+z} \quad \text{for } z = [\text{CH}_4] \text{ in microlitres per litre}$$

Key	PD	Partial discharges
D1	Discharges of low energy	
D2	Discharges of high energy	
T1	Thermal fault, $t < 300^\circ\text{C}$	
T2	Thermal fault, $300^\circ\text{C} < t < 700^\circ\text{C}$	
T3	Thermal fault, $t > 700^\circ\text{C}$	

Limits of zones				
PD	98 % CH ₄			
D1	23 % C ₂ H ₄	13 % C ₂ H ₂		
D2	23 % C ₂ H ₄	13 % C ₂ H ₂	38 % C ₂ H ₄	29 % C ₂ H ₂
T1	4 % C ₂ H ₂	10 % C ₂ H ₄		
T2	4 % C ₂ H ₂	10 % C ₂ H ₄	50 % C ₂ H ₄	
T3	15 % C ₂ H ₂	50 % C ₂ H ₄		

Figure B.3 – Graphical representation 3 of gas ratios –
Duval's triangle (see [5] of annex C)

Annex C
(informative)

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- [4] COUDERC et al., CEIDP San Francisco, 1996
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- [6] IEC 60050(321):1986, *International Electrotechnical Vocabulary (IEV) – Chapter 321: Instrument transformers*

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